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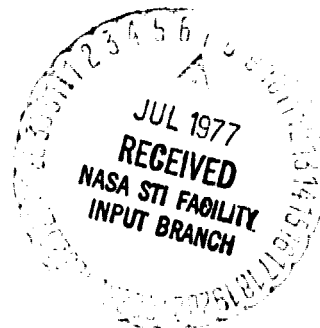
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IN FILM-COOLED TURBINE VANES (NASA) 23 P HC
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**PLUGGING OF COOLING HOLES IN
FILM-COOLED TURBINE VANES**

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16. Abstract The plugging of vane cooling holes by impurities in a marine gas turbine was closely simulated in burner rig tests where dopants were added to the combustion products of a clean fuel (Jet-A). Hole plugging occurred when liquid phases, resulting from the dopants, were present in the combustion products. Increasing flame temperature and dopant concentration resulted in an increased rate of deposition and hole plugging.					
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SUMMARY

Burner rigs were used to expose film air-cooled vanes to combustion products doped with the same elements found in the fuel and air used in a marine gas turbine engine test stand where severe hole plugging occurred. The dopants, flame temperature, and vane temperature were test variables. Deposition and hole plugging were monitored by weight gain and leading-edge temperature rise, respectively. The deposits were analyzed by XRD, metallography, and SEM.

The engine deposits were closely simulated by the burner rig in terms of appearance, location, structure, and phase and elemental composition when the dopants were iron, calcium, and phosphorus. Other dopant combinations were found to also cause hole plugging. The common requirement for hole plugging appeared to be the presence of a liquid phase in the flame. Plugging increased with flame temperature and dopant level as well as with concentration.

INTRODUCTION

As turbine inlet temperatures have been pushed higher and higher, metal blades and vanes have relied increasingly on air cooling to keep metal temperatures low enough for adequate air foil rupture life (ref. 1). Loss of such cooling could result in drastically premature failure of the blades and/or vanes, especially those of the first turbine stage where temperatures are highest. Film cooling, one of the more advanced cooling schemes, relies on the flow of compressor air through the inside of the airfoil and out through small holes located at critical areas of potential high temperature, for example, the leading edge. If these holes were to be plugged for any reason, cooling flow would be substantially reduced and an unacceptable rise in temperature would result. Failure could result from either excessive temperature/stress levels or melting.

Such plugging has been noted by the Navy in one of their engine test stands

(data obtained from G. B. Katz of Naval Ship Engineering Center). They noted thick (up to 0.8 mm) deposits rich in iron, covering the surface of first-stage blades and vanes. In many areas, but especially on the leading edge, the cooling holes were completely covered. The times required for these extensive buildups were in excess of 1000 hours although substantial deposits were noted in several hundred hours. The source of the deposits was not established, but it was noted that iron was present in the air and the fuel at levels of parts per million.

One of the vane pairs from these tests was obtained by the authors and evaluated metallographically, by X-ray diffraction (XRD), and spectroscopically. The results of these analyses, in general, confirmed the findings of Katz. However, in addition to the iron oxide phase he reported, large amounts of another phase, identified by X-ray diffraction as $(\text{Ca}, \text{Mg})_4\text{Fe}_5(\text{PO}_4)_6$, were found in the deposit. This identification was supported by spectrochemical identification of P, Mg, and Ca in the deposit. The source of the phosphorus is not clear although zinc dithiophosphate is often used as a fuel additive to diesel fuel as a low-temperature corrosion inhibitor. It is possible that low levels of phosphorus could result from contamination of the fuels while in refinery storage containers previously used for fuels so treated.

The purposes of the work described in this report are twofold: first, to duplicate the deposit formation under closely controlled conditions and second, to identify the variables important to deposition and plugging. The approach used was to heat a single vane in a burner rig holding the cooling air pressure constant. Potential deposit-forming materials were introduced as a water solution of their salts into the combustion chamber. The tests were accelerated by using relatively high levels of these elements. Any "accelerated" test is open to question on the grounds that the methods used to accelerate may also change the mechanism resulting in an invalid test. In this case, however, as will be seen below, the deposits formed in the burner rig test were similar to the actual engine test in location, morphology, and composition. In addition, preliminary rig runs were made in which the concentration of the dopants was found to be proportional to the deposition rate. From these results it was concluded that the use of increased dopant concentration was a valid accelerating technique.

The effects of deposition were determined by the rate of deposit (ΔW) and the rise in temperature of the leading edge (ΔT). The nature of the deposit was

evaluated by metallography, scanning electron microscopy (SEM) in conjunction with energy dispersive analysis (EDS) and X-ray diffraction (XRD).

MATERIALS AND PROCEDURES

The experimental arrangement is shown schematically in figure 1 and in a photograph in figure 1(b). Dopants were added as an aqueous salt solution directly to the combustion chamber where clean A-1 jet fuel was burned. Dopant concentrations were expressed as parts per million by weight of the combustion products. The doped combustion products were exhausted through the nozzle, exiting at Mach 0.3 and striking the vane normal to the leading edge. The vane was cooled by flowing air at ambient temperature in the ends of the vane and out the film cooling holes. The cooling air pressure (usually $\sim 1.1 \text{ N/M}^2$ (1.5 psi gage)) was fixed for the duration of the run. The vanes were weighed before the start of the run and at intervals during the run. The leading-edge temperature was monitored optically to $\pm 10^\circ \text{ C}$ throughout. Typically, the temperature rose rapidly at the start of the run as cooling holes plugged and leveled out after several hours. Once a constant leading-edge temperature was established, the run was terminated. The severity of hole plugging was judged by the temperature rise (ΔT). At the conclusion of the test the vanes were sectioned near the mid point and evaluated by metallography, SEM, and XRD.

The dopants to the combustion products used in this program were determined by considering air and fuel impurities and the composition of the deposits found on the vane tested by the Navy. Tables I and II summarize this information. The major impurities found in the fuel or air and also in the deposit were iron, calcium, magnesium, phosphorus, and zinc. All but zinc were introduced as dopants in this work. In addition some runs were made with silicon as it is the major impurity in the combustion air and was found in the deposits by Katz. A summary of the dopants and their levels is given in table III. Most runs concentrated on combinations of iron, calcium, and phosphorus as these were the major constituents, except for magnesium, in the phases found by XRD. Further, there are some low melting point phases possible in the $\text{Fe}_2\text{O}_3\text{-CaO-P}_2\text{O}_5$ system (see fig. 2). It was felt that magnesium would behave similarly to CaO although higher melting points might be expected in magnesium containing oxide systems (fig. 3). This behavior was

confirmed (see below). Melting point of the deposit was felt important because it was expected that liquid phase formation in the flame would be critical to hole plugging.

Starting leading edge and the calculated adiabatic flame temperatures were 815° and 1530° C, respectively. The initial cooling air flow was set to that required to achieve the desired initial leading-edge temperature for a given flame temperature and the cooling air pressure was held constant for the duration of the test. The variations in these parameters are shown in table III.

RESULTS AND DISCUSSION

Burner Rig Sample Environment Assumptions

In the following sections several assumptions about the mechanism by which dopants deposit on the blade have been made. These will be outlined in this section. The main assumption made was that a liquid phase(s) was present either in the flame or condensed from the combustion products on to the cooler vanes when hole plugging occurred. For relatively simple systems (e.g., Fe as the sole dopant), thermodynamic calculations can be made using the program developed in reference 3. The composition of the combustion products can be so calculated at the adiabatic flame temperature and at the lower temperatures found on and near the vane. These calculations show solid Fe_2O_3 to be the only condensed phase in the combustion products from 1530° C down to 815° C. Since hole plugging was not observed (see below) under such conditions, although deposition of Fe_2O_3 was observed, it was concluded that the air flow through the holes was sufficient to sweep the holes clean. Due to a lack of thermodynamic data, similar calculations could not be made for the more complex doping cases involving Fe, Ca, and P. The assumption is made, however, that in these cases condensed liquid phases are formed either in the combustion zone or at cooler portions of the gas downstream of the burner rig but before the vane is reached. That this is the case seems to be confirmed by the morphology of the deposits which plug cooling holes; these deposits definitely appear to have been, at least in part, liquid (see below). Since, as mentioned, exact calculations cannot be made, the presence or absence of liquid phase formation was implied from the limited phase diagram information available (figs. 2 and 3). Fortunately, deposit formation was found to correlate reasonably well with

expected liquid phase formation. In summary, while little a priori evidence could be found to support the assumptions, the experimental results seem consistent with these assumptions.

Deposition Pattern

The appearance of the Navy engine tested vane (fig. 4) was characterized by a rust-colored irregular deposit which was heavy on the leading edge and high-pressure surface and very light on the low-pressure surface. The heaviest deposit on the high-pressure surface was located about 2/3 of the way toward the trailing edge. In regions of heaviest deposit, cooling holes were almost obliterated. When conditions in the burner rig were appropriate for heavy deposit formation (figs. 5(a) and (b)) similar patterns were noted: heavy deposits formed on the leading edge and high-pressure face especially about 2/3 of the way down, and light deposits formed on the trailing edge and low-pressure surface. These similarities built confidence in the validity of using an atmospheric burner rig test for simulation of deposition in a high-pressure turbine engine; the two types of tests appear to be qualitatively the same. Figure 5 typifies the two types of results obtained. In the burner rig run made with Fe, Ca, and P (a and b), liquid phases were expected during combustion, and heavy deposits and obvious hole plugging were observed. In the run made with only iron (c and d), no liquid phase was expected and only light deposits with little or no plugging were observed.

ΔW and ΔT

The weight change and leading-edge temperature rise data are summarized in table III. Run 1 was simply a test to determine whether or not the fuel itself (Jet-A) could be a source of deposition and to test how well the temperature of the vane could be held constant. No deposit was found in 100 hours and there was no measurable change ($\pm 10^\circ \text{C}$) in temperature. Runs 2 (2 ppm Fe) and 3 (10 ppm Fe) used no air cooling and were only used to show that deposition rate was somewhat proportional to dopant concentration.

The ΔT of run 4 (2 ppm Fe) is plotted on figure 6. There appears to be a slight rise, but it is almost within the scatter in the data ($\pm 10^\circ \text{C}$). The vane used in this run is shown in figures 5(c) and (d) and shows little visual evidence

of plugging, as mentioned above. Runs 5 and 6 (both 2 ppm Fe + 1/2 ppm Ca) should have formed a liquid phase in the flame (see fig. 2) and both runs show substantial increases in ΔW and ΔT over run 4. The higher flame temperature in run 6 accelerated ΔW and increased ΔT .

Runs 7 to 9 (all 2 ppm Fe + 1/2 ppm Ca + 1 ppm P) confirm the effect of flame temperature on ΔW and ΔT , but also show that the addition of phosphorus greatly enhances the deposition rate; a comparison of run 6 with run 9 shows that less than a third more total dopant in the form of phosphorus triples ΔW and almost doubles ΔT (see figs. 6 and 7). Run 10 (2 ppm Fe + 1/2 ppm Mg + 1 ppm P) shows that magnesium appears to have the same effect as calcium, while runs 11 and 12 show that varying the calcium and phosphorus levels has little effect on ΔT but considerable effect on ΔW . The reason for the apparent upper limit on ΔT is that the flame pattern, as visually observed, does not cover the entire leading edge so that with a maximum deposition rate some holes will not be covered. When all the holes that are within the flame pattern are covered, no further loss in cooling can occur and no greater rise in leading-edge temperature will be experienced.

The remaining runs (Fe with Si, Fe with Si and Ca, and Fe with Pb and Ca) give further indications that a liquid phase must be present for hole plugging to occur. The Fe + Si run showed little evidence of hole plugging while the addition of Ca resulted in lower melting compounds and substantial ΔW and ΔT . The Fe, Pb, Ca run was intermediate in ΔW and ΔT . It does not appear to matter, to a first approximation, what liquid phase is present. As long as some liquid is in the gas stream, plugging is thought to be likely.

METALLOGRAPHY, XRD, AND SFM

Figure 8 shows the microstructures of several deposits in and near a leading-edge hole. Parts a and b give a direct comparison between the deposit on a vane from the engine test with the burner rig produced deposit. Both deposits are porous and extensive, completely filling the cooling hole. Both deposits have similar major constituents (see table II) and both deposits have major amounts of Fe_2O_3 and $(\text{Ca, Mg})_4\text{Fe}_5(\text{PO}_4)_6$ although in the burner rig deposit the Mg level is zero in the phosphate phase. These data combined with the appearance of the vane as well as ΔW and ΔT data strongly suggest that the burner rig tests have closely simulated the conditions in the engine on an accelerated basis.

The rest of figure 8 serves to show that such deposits can form from a variety of dopant compositions. Increasing the phosphorus level yields a deposit which is quite glassy (fig. 8(c)), while increasing calcium levels increases granularity (fig. 8(d)). The Mg-Fe-P deposit (fig. 8(d)) is similar to the deposit resulting from doping with Ca-Fe-P. Finally, figure 8(f) shows that similar deposits can occur with only Fe and Ca.

One interesting feature which is shown by these microstructures is the severe deposit cracking and spalling shown on all samples. This spalling is primarily due to thermal expansion mismatch between deposit and vane. This might be thought to be helpful; however, it appears that while the outer surface deposit may spall off, the deposits in the holes remain locked in place (see especially fig. 8(c)). Thus, while the addition of thermal cycling would substantially alter the measured ΔW , it might have little effect on the plugging of cooling holes and hence ΔT .

CONCLUSIONS

As a result of doping combustion products during burner rig testing of air-cooled vanes, the following conclusions may be drawn:

(1) Burner rigs can be used to accelerate the formation of deposits on air-cooled vanes. Deposits result that closely simulate those formed in engine tests in terms of appearance, location, and composition.

(2) A liquid phase must be present in the combustion gases before cooling hole plugging is likely to occur although deposition without plugging may occur if only solid phases are present.

(3) Higher flame temperatures appear to increase deposition rates, although more work would be required to establish a precise flame temperature/deposition rate relationship.

RECOMMENDATIONS

Interest in hole plugging is usually limited in aircraft turbines due to their use of relatively clean fuels. Marine turbines, which operate on less clean fuels, may elicit more interest in this phenomenon. However, air-cooled advanced ground power turbines may use "dirtier" fuels which will require considerable

attention to the deposition phenomena. Particularly important will be a greater knowledge of the effects of fuel or air impurities other than the ones investigated in this report with emphasis on elements which might form glasses with the SiO_2 in the air. At the same time it might be possible to find additives which would raise the melting points of compounds formed during combustion to eliminate the plugging entirely. The effects of vane and flame temperatures on plugging also need careful investigation along with pressure effects. Of equal importance would be an understanding of the mechanism and kinetics of deposition, a field which has, until recently, received scant attention. Finally, the effect of deposits on cooling efficiency should be determined on other types of cooled blades, that is, transpiration and full-coverage cooling. This work could be combined with efforts to reduce plugging by design changes, for example, hole size, geometry, and angle.

REFERENCES

1. Suciu, S. N.: High Temperature Turbine Design Considerations. SAE Paper 710462, May 1971.
2. Levin, Ernest M.; Robbins, Carl R.; and McMurdie, Howard F.: Phase Diagram for Ceramists. The American Ceramic Society, 1964.
3. Gordon, Sanford; and McBride, Bonnie J.: Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations. NASA SP-273, 1971.

**TABLE I. - COMPOSITION OF FUEL AND AIR
IMPURITIES FROM NAVAL ENGINE TEST**

(a) Fuel - marine diesel

Element	Sample date		
	2/6/76	2/12/76	2/18/76
Sulfur, w/o	0.38	0.36	0.37
Iron, ppm	.96	1.37	1.89
Copper, ppm	1.68	1.17	.85
Zinc, ppm	.51	.55	.57
Lead, ppm	3.03	3.03	4.53
Magnesium, ppm	4.13	5.22	4.13
Calcium, ppm	.048	.098	.048
Phosphorus, ppm	<.5	<.5	<.5
Silicon, ppm	N.D. ^a	N.D.	N.D.

(b) Typical analysis of airborne particles

Major: Silicon (≥10%)
Minor: Iron, sodium, aluminum, calcium, magnesium, lead (10-0.1%)
Trace: Antimony, boron, copper, manganese, nickel, silver, tin, titanium, vanadium, zinc (<0.1%)

^aNot detected.

**TABLE II. - SPECTROCHEMICAL ANALYSIS
OF VANE DEPOSITS**

Element	Navy engine	Lewis rig tested vane dopant 2 Fe - 1/2 Ca - 1 P
Fe	20	33
Ca	49	14
P	7	50
Mg	12	----
Si	<.1	----
Ni	.4	1.4
Co	.5	1
Cr	----	.2
Cu	----	.1
Mn	----	.2
Al	1	----
K+Na	<1	----
Zn	8	----

Note: All values are in weight percent and are normalized to 100% metal and are $\pm 10\%$.

TABLE III. - SUMMARY OF RUN CONDITIONS AND RESULTS

Run	Additive, ppm	Vane cooling air flow, kg/min	Leading-edge temperature start, °C	Flame temperature, °C	ΔW deposition rate, mg, hr ⁻¹	ΔT leading-edge temperature rise, °C	Test duration, hr
1	None	0.26	815	1530	0	0	100.0
2	2 Fe	0	800	820	4	---	68.0
3	10 Fe	0	800	820	13	---	35.0
4	2 Fe	0.26	815	1530	4	30	27.6
5	2 Fe, 1/2 Ca	.26	815	1530	9	80	10.0
6	2 Fe, 1/2 Ca	.30	815	1700	19	110	8.3
7	2 Fe, 1/2 Ca, 1 P	.26	^a 680	1000	16.3	---	7.4
8	2 Fe, 1/2 Ca, 1 P	.26	^a 730	1200	26.3	110	7.8
9	2 Fe, 1/2 Ca, 1 P	.26	815	1530	60	200	28.7
10	2 Fe, 1/2 Mg, 1 P	.26	815	1530	60	170	7.2
11	2 Fe, 1/2 Ca, 2 P	.26	815	1530	80	190	6.4
12	2 Fe, 2 Ca, 1 P	.26	815	1530	30	210	13.8
13	2 Fe, 1/2 Si	.26	815	1530	6	30	8.1
14	2 Fe, 1/2 Si, 1 Ca	.26	815	1530	28	140	8.1
15	2 Fe, 1/2 Pb, 1 Ca	.26	815	1530	16	80	8.2

^aBy extrapolation.

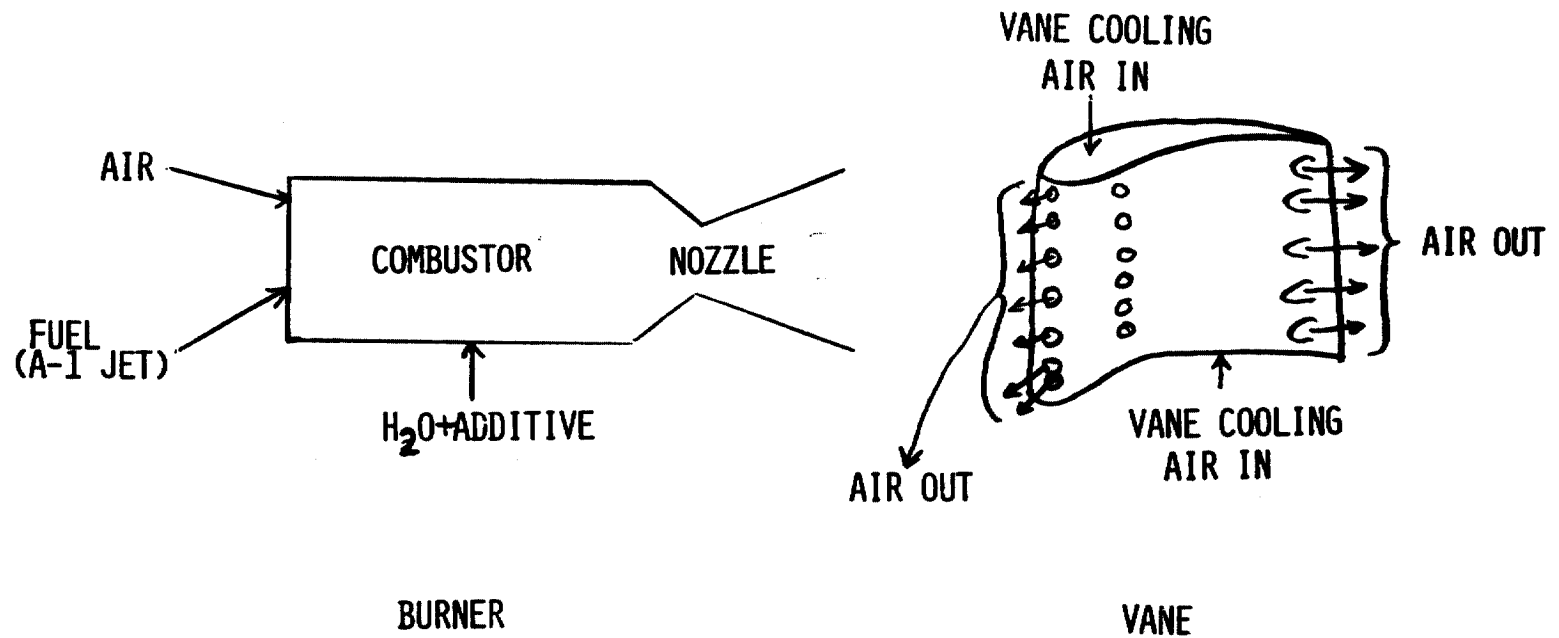


FIGURE 1A. SCHEMATIC DIAGRAM OF BURNER RIG

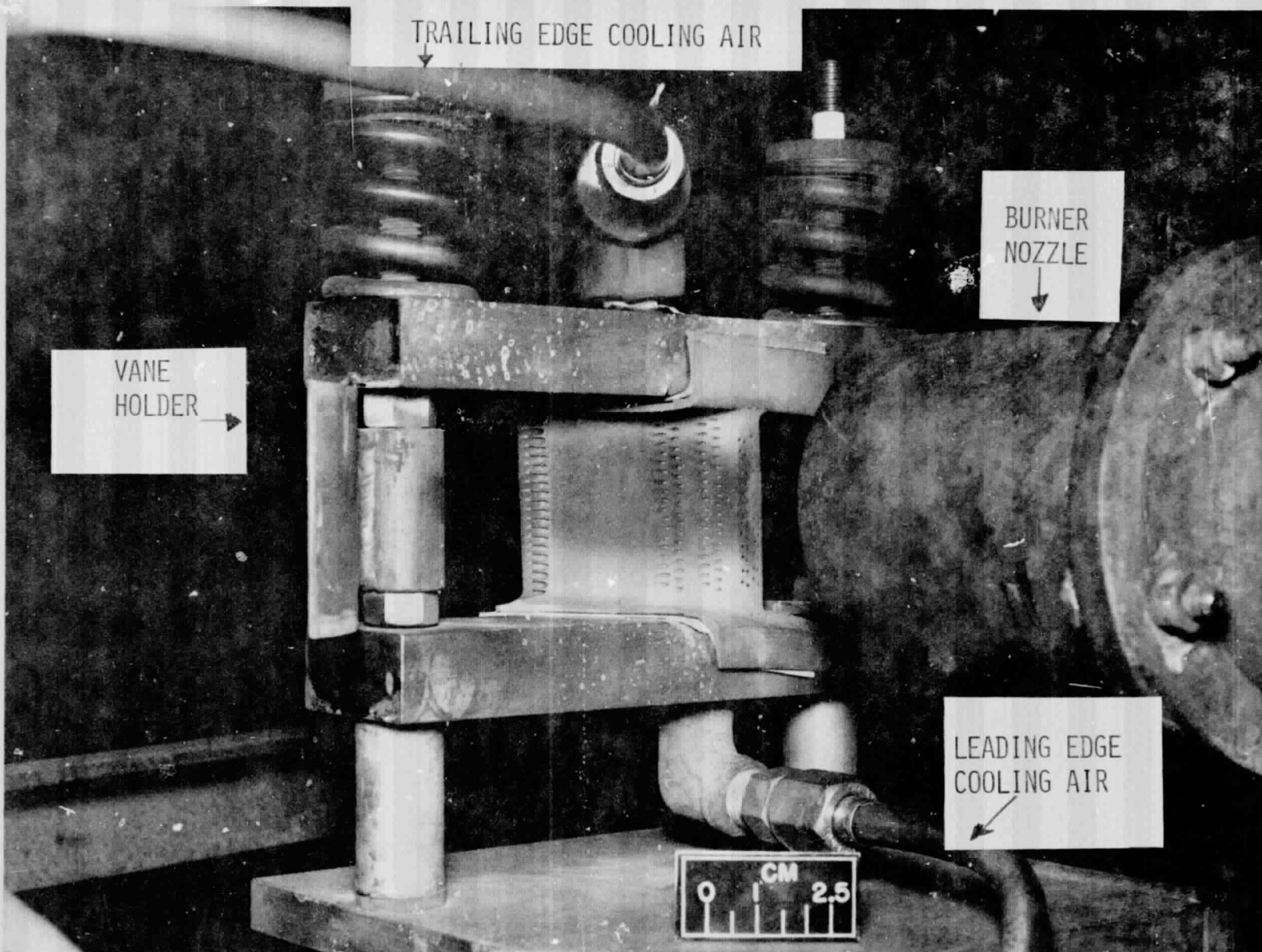


FIGURE 1B. PHOTOGRAPH OF TEST ARRANGEMENT

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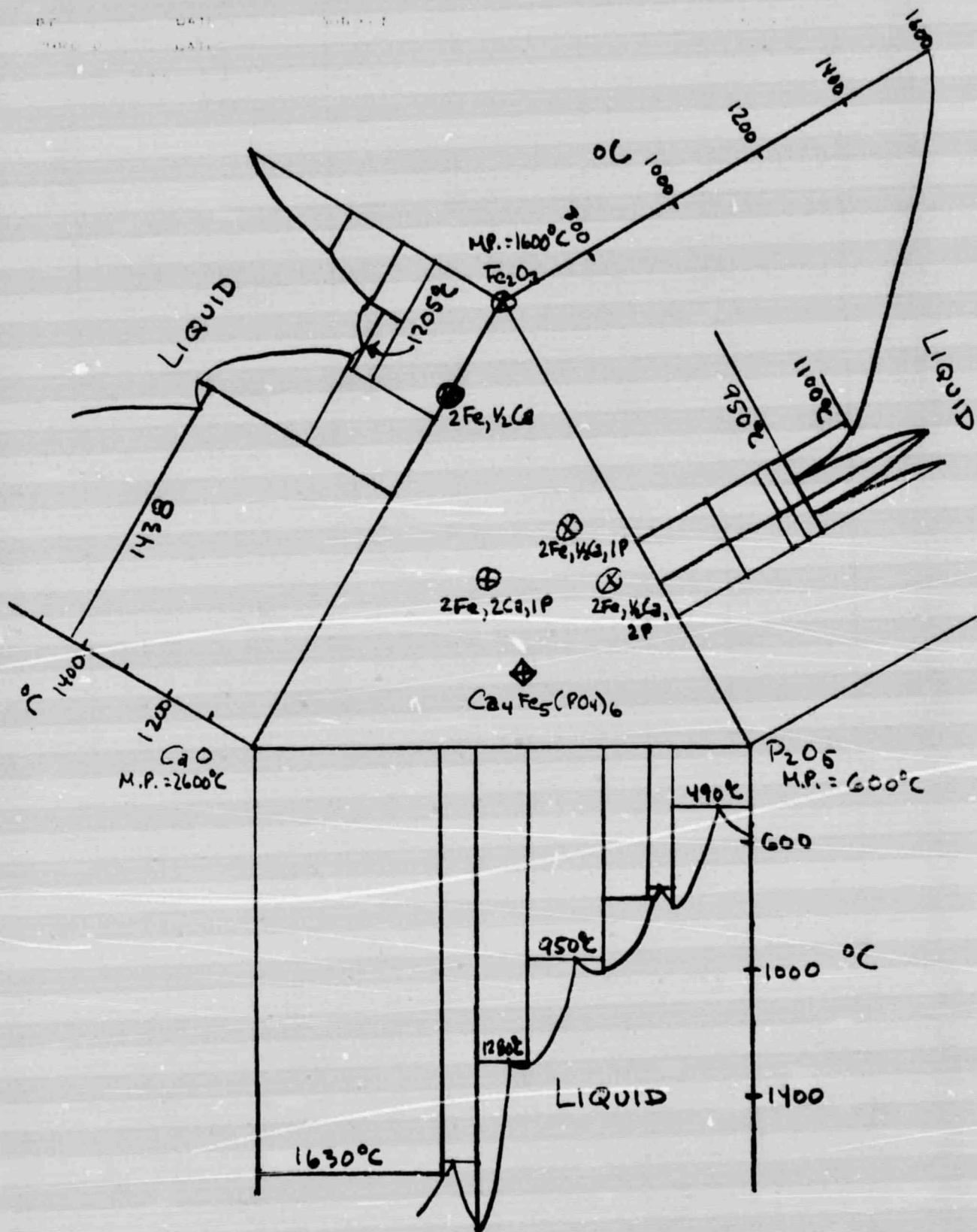
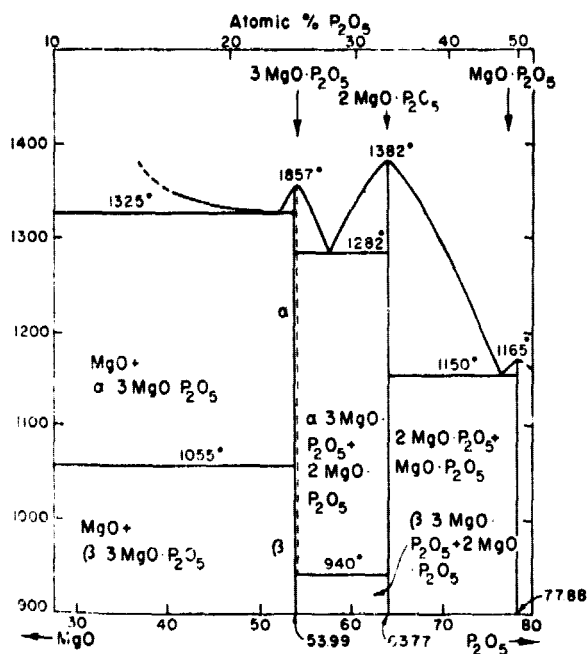
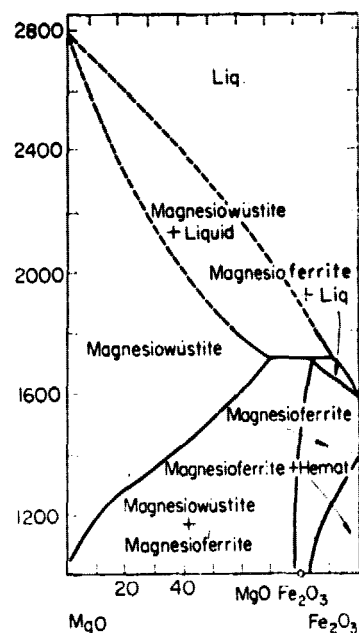


FIGURE 2. SOME MELTING POINT DATA IN THE Fe_2O_3 - CaO - P_2O_5 SYSTEM AND THE APPROXIMATE DOPANT COMPOSITIONS. (REF 2)



A. MgO-P₂O₅ SYSTEM

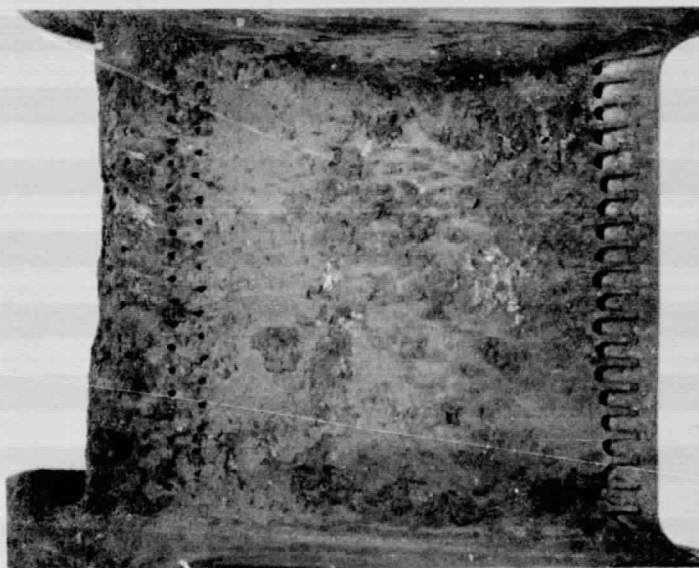


B. MgO-Fe₂O₃ SYSTEM

FIGURE 3. SOME PHASE DIAGRAMS IN THE Mg-Fe-P-O SYSTEM (REF. 2)



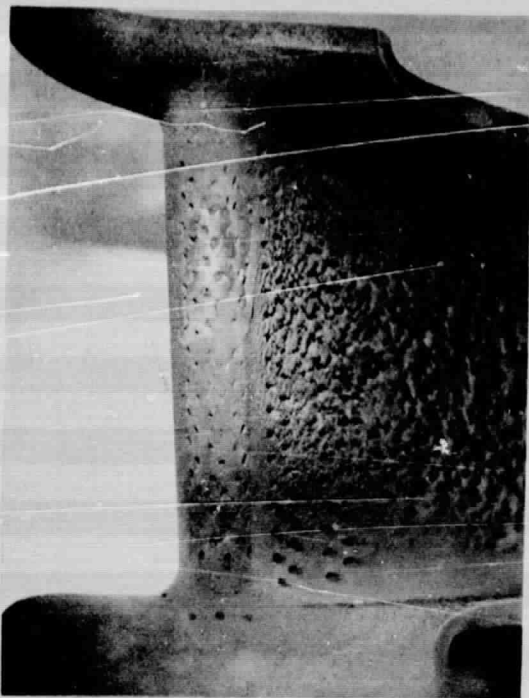
LEADING EDGE



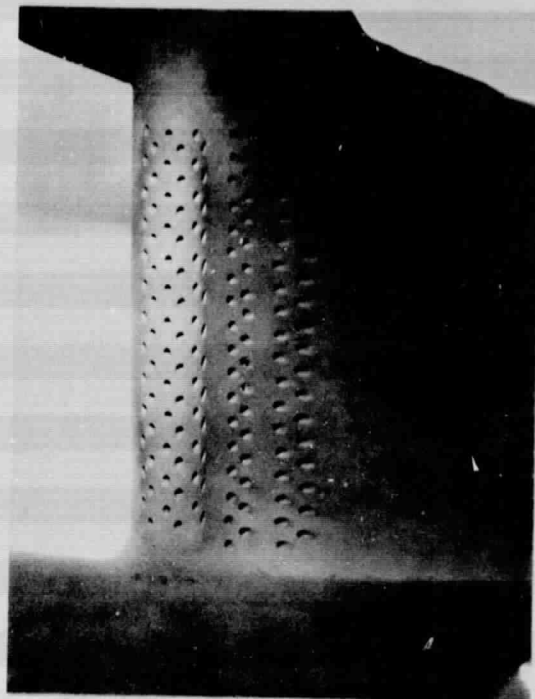
PRESSURE FACE

FIGURE 4. DEPOSITS AND COOLING HOLE PLUGGING OF VANE
FROM ENGINE TEST STAND, FUEL-DIESEL #2.

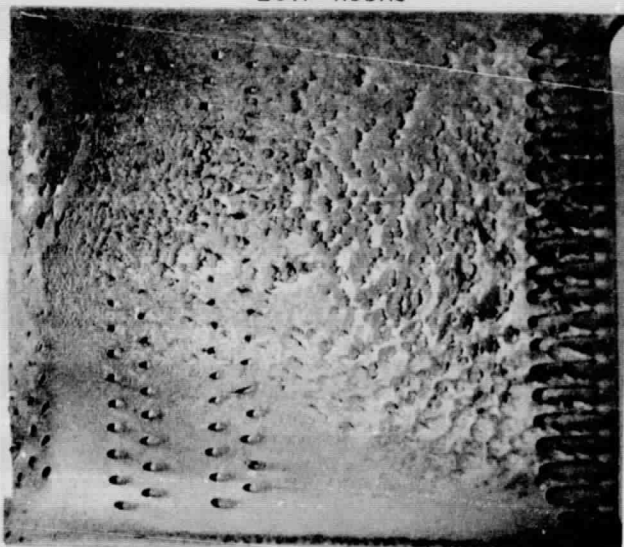
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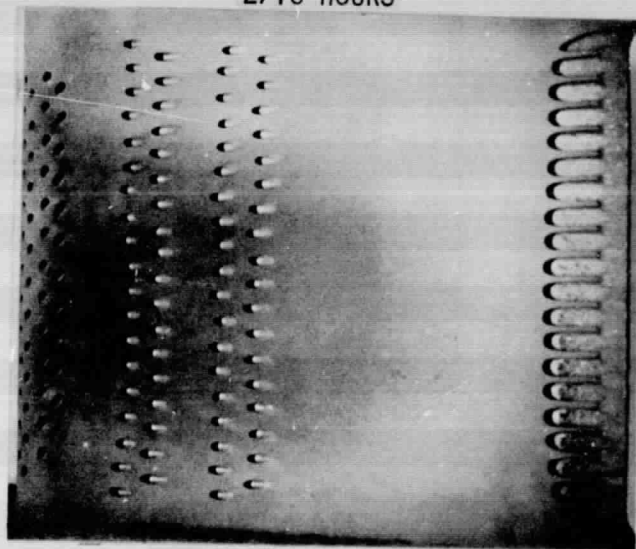
A. LEADING EDGE - 2PPM Fe, 1/2 CA, 1P
28.7 HOURS



C. LEADING EDGE - 2PPM Fe
27.6 HOURS



B. PRESSURE FACE - 2 PPM Fe, 1/2 CA, 1P
28.7 HOURS
T=200°C



D. PRESSURE FACE - 2PPM Fe
27.6 HOURS
T=30°C

FIGURE 5. DEPOSITS AND COOLING HOLE PLUGGING IN MACH 0.3 MACH 0.3
COMBUSTION PRODUCTS DOPED AS NOTED. LEADING EDGE
EDGE TEMPERATURE AT START=815°C, 0.26 KG/MIN COOLING AIR,
FLAME TEMPERATURE=1530°C

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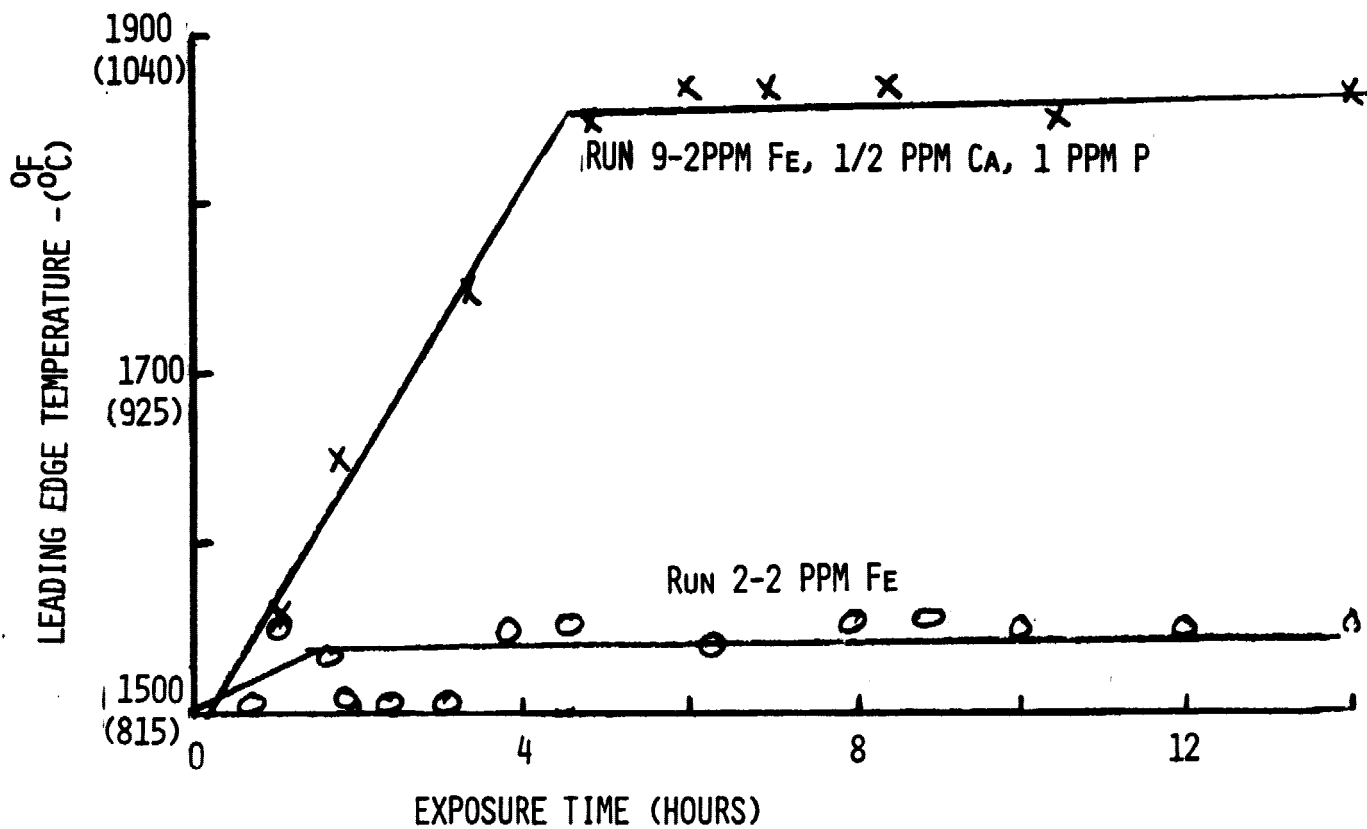


FIGURE 6. THE EFFECT OF DEPOSITION AND RESULTANT LOSS OF COOLING IN TWO TYPICAL RUNS.

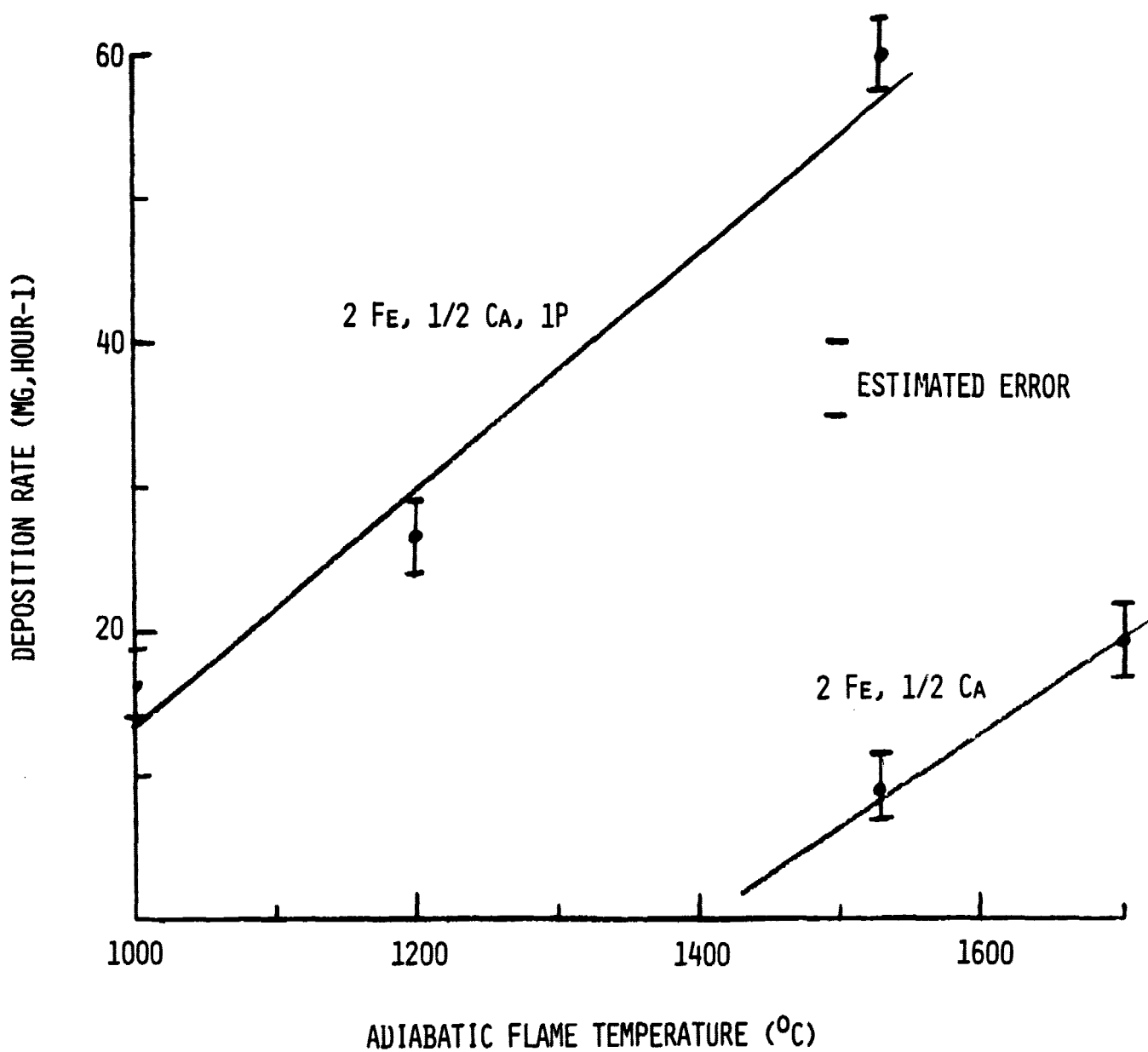
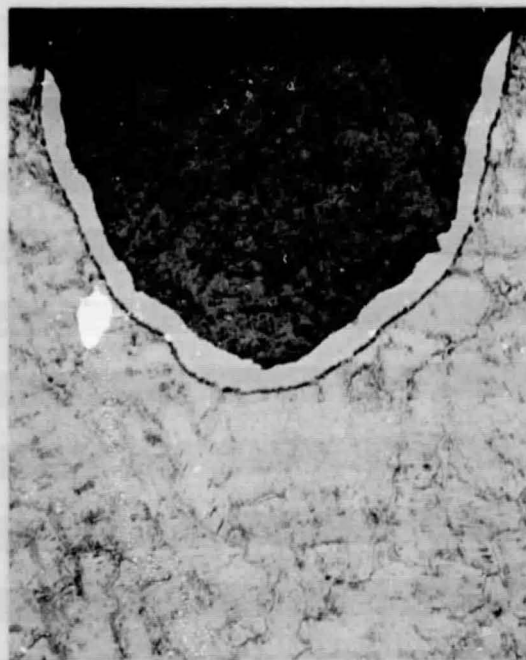


FIGURE 7. EFFECT OF FLAME TEMPERATURE ON DEPOSITION RATE



A. ENGINE TEST #2 DIESEL 100X
1000 HOURS



B. MACH 0.3 TEST 2Fe, 1/2 Ca, 1 P 100X
14.2 HOURS



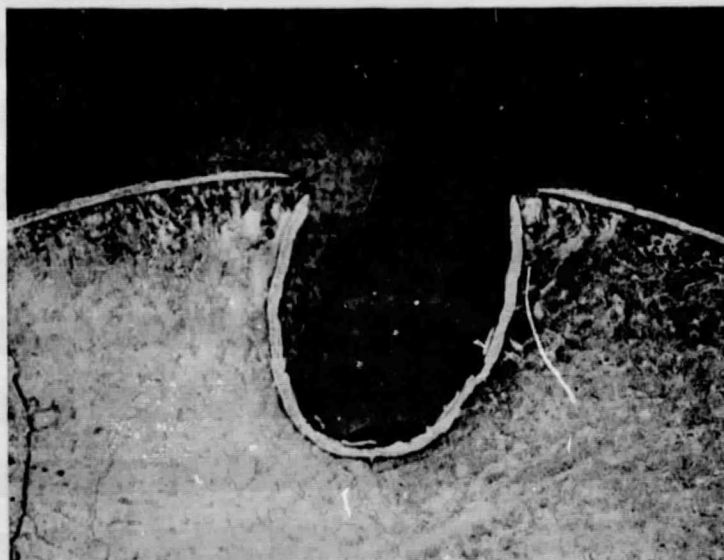
C. MACH 0.3 TEST 2Fe, 1/2 Ca, 2P 50X
6.4 HOURS



D. MACH 0.3 TEST 2Fe, 2Ca, 1P 50X
13.8 HOURS

FIGURE 8. MICROSTRUCTURE OF DEPOSITS FORMED IN MACH 0.3
COMBUSTION PRODUCTS DOPED AS NOTED COMPARED TO THOSE
FORMED DURING AN ENGINE TEST USING NUMBER TWO DIESEL
FUEL.

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E. MACH 0.3 TEST $2\text{Fe}, 1/2\text{Mg}, 1\text{P}$ 50X
7.2 HOURS



F. MACH 0.3 TEST $2\text{Fe}, 1/2\text{Ca}$ 50X
10.0 HOURS

FIGURE 8. CONTINUED

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